The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting

J.R. Williamson and W.A. Neilsen

Abstract: Soil compaction has been considered a principal form of damage associated with logging, restricting root growth and reducing productivity. The rate and extent of soil compaction on skid trails was measured at six field locations covering a range of dry and wet forests. Data was collected for up to 21 passes of a laden logging machine. A similar extent of compaction, averaging 0.17 g·cm^{-3} increase in total soil bulk density (BD), was recorded for all field sites despite substantial site and soil differences. On average, 62% of the compaction in the top 10 cm of the soil occurred after only one pass of a laden logging machine. The environment under which soils had formed played a major role in determining the BD of the undisturbed soil. Compaction was strongly related to the original BD, forest type, and soil parent material. Soil strengths obtained in the field fell below levels found to restrict root growth. However, reduction in macropores, and the effect of that on aeration and drainage could reduce tree growth. On the wettest soils logged, machine forces displaced topsoils rather than causing compaction in situ. Recommended logging methods and implications for the development of sustainability indices are discussed.

Résumé : La principale forme de dommages associés à l'exploitation forestière est le compactage du sol qui restreint la croissance des racines et réduit la productivité. Le taux et l'étendue du compactage du sol sur les sentiers de débardage ont été mesurés sur le terrain à six endroits représentatifs d'une gamme de forêts sèches et humides. Les données ont été collectées pour jusqu'à 21 passages d'une machine d'exploitation chargée. Un degré de compactage similaire, qui représente une augmentation moyenne de 0,17 g·cm^{-3} de la densité apparente totale (BD), a été enregistré à tous les sites en dépit des différences substantielles entre les sites et entre les sols. En moyenne, 62% du compactage dans les premiers 10 cm de sol s'est produit après le premier passage d'une machine d'exploitation chargée. L'environnement dans lequel les sols se sont formés, a joué un rôle majeur dans la détermination de la densité apparente du sol non perturbé. Le compactage était fortement relié à la BD originale, au type forestier et au matériel d'origine. La résistance du sol obtenue sur le terrain a diminué en dessous du seuil qui permet aux racines de croître sans restrictions. Cependant, la réduction des macropores et ses effets sur l'aération et le drainage peuvent réduire la croissance des arbres. Sur les sols les plus humides ayant été exploités, la friction des machines a déplacé la couche supérieure du sol au lieu de compacter le sol sur place. Les méthodes d'exploitation recommandées et les implications pour le développement d'indices de durabilité sont discutées.

[Traduit par la Rédaction]

Introduction

Soil compaction has been reported as the principal form of damage associated with harvesting traffic (Hatchell et al. 1970; Dickerson 1976). Compaction increased soil bulk density (BD), decreasing water and air movement into and through the soil profile, restricting root growth through mechanical impedance, and increasing surface runoff and erosion (Reinhart 1964; Greacen and Sands 1980; Rab 1996). Along skid trails, productivity was often reduced with lower tree stocking and reduced growth (Young et al. 1967; Moehring and Rawls 1970; Wert and Thomas 1981; Lockaby and Vidrine 1984). Organic matter removal and disturbance of part, or all, of the A horizon was associated with poor regeneration on skid trails (Calais and Kirkpatrick 1983; Wronski 1984).

Bulk density's restriction of root growth varied with soil type (Reisinger et al. 1992). Froehlich et al. (1986) found no effect of BD increases on growth of stands to 9–13 years of age on light-textured soils of initial low BDs (<1.0). On fine-textured soils of low initial BD compaction of 41–52% did not significantly affect growth of planted seedlings, to age 8 years (Miller et al. 1996). Farish et al. (1995) determined a 17% reduction of growth on compacted ruts, but this was not significant. Corns (1988) measured significantly reduced growth as a result of compaction.

The susceptibility of soil to compaction strongly depended on the soil moisture content (Moehring 1970; Froehlich 1972), soil organic matter (OM) content (Adams 1973; Howard et al. 1981), soil type (Hatchell et al. 1970), the number of machine passes (Jackobsen 1983; Soane 1986), the volume of timber hauled (Greacen and Sands

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1980), the load applied, and the characteristics of the machine applying the load (Porterfield and Carpenter 1986). Most of these factors were dynamic and depended on the operation thus making it difficult to evaluate the contribution of each factor.

Information on the degree of compaction from normal logging operations and its effect on forest growth are needed to determine if current management of forests is sustainable. Measurement of change in BD is being suggested as one indicator for monitoring sustainable management (Rab 1999). The relationship of BD to forest site and soil characteristics and the effect of these on compaction by logging traffic were studied in a number of trials undertaken in Tasmania. The rate and extent of soil compaction was measured under controlled conditions at a number of field locations.

Methods

Sites

Six locations were selected covering a range of vegetation, rainfall, and soil types (Table 1). Soils varied markedly ranging from heavy clay soils to gravely sandy soils (Table 2). Soils were selected based on three site types each with two experimental sites (Table 1). The site types were dry forest with low rainfall, wet forest with high rainfall, and wet forest with very high rainfall. One of the soils under very high rainfall was a deep medium clay-loam, while the other was an organic soil over sandy loam with a total depth of only 23 cm. Initial BDs were highest under the dry forest and lowest under the wet forest with very high rainfall.

Machine operations

As a base for the research a three-tier visual classification system was used to stratify soil damage levels (Wronski 1984) (Table 3). The visual condition of the skid trail following each sampling time was assessed according to these three classes. Visual condition was used as an estimate of profile disturbance.

The rate of compaction of soil on skid trails was studied from an undisturbed state through to 21 passes, where possible, of a laden logging machine (Table 4). On one of the sites, only 15 passes were made, while primary damage was sustained after only 3 passes at Picton, and a total of only 6 passes were made. The mass of logs hauled during each trial was similar, the average size being 1.5 m^3 (Table 4). At the time of treatment, soils were moist but not saturated. There was considerable variation in the moisture content of the various soils. On four of the sites, logging was completed once in summer and once in winter. However on three of the sites moisture conditions were similar on both occasions (Table 1).

Skid-trail sampling and soil cores

On each logged area, an undisturbed area 5 × 20 m was selected adjacent to a major skid trail. Each area was cleared of large vegetation by hand. Samples were taken following clearing but prior to any machine activity (control) and after 1, 3, 6, 10, 15, and 21 passes of a laden skidder. A machine pass was defined as a single one-way trip. There was no replication at sites.

At each sampling time, sets of undisturbed soil cores were taken at four sites, two randomly located on each wheel rut. Each set consisted of cores taken at 0–10, 10–20, and 20–30 cm. Intact soil samples were removed using steel cores, 10 cm high, 7.5 cm internal diameter (417 cm^3) with a wall thickness of 1.6 mm. The cores were driven into the soil using a falling weight hand corer. BD and gravimetric moisture content were determined from the cores.

Bulk density, soil organic matter content, and soil strength

The volume of any missing soil occurring in the top or bottom of the core was estimated gravimetrically using sand with a constant volume to weight ratio. This volume was subtracted from the standard core volume. Bulk density was calculated using oven-dry soil (Blake 1965).

A 100-g sample of soil was removed adjacent to each core location for OM estimation by loss on ignition (LOI). A 25-g sample of oven-dry soil (105°C) was burned in a furnace at 600°C for 4 h. LOI was determined gravimetrically.

Soil strength was measured using a stainless steel, falling-weight penetrometer with shaft diameter of 6 mm and conical tip of 60° with recess behind the tip. The shaft was driven with a 1-kg weight falling 50 cm, strength being measured by the number of hits to drive the penetrometer in 10-cm increments. Forty measurements along each wheel rut were taken to a depth of 30 cm.

Hydraulic conductivity

In the laboratory, constant-head saturated hydraulic conductivity was measured for all sites except Picton using the method of McIntyre and Loveday (1974). Cores, 10 cm high and 7.5 cm wide, were repacked to BDs similar to those recorded in the field. On all soils tested, wide variations in hydraulic conductivity (K) were recorded at the same BD level. To transform the data, the geometric mean (K_g) was calculated on the assumption of a log-normal distribution. Using this distribution, the anti-logarithm of the standard deviation (S_L) was used as an index of variability (Rogowski 1972; Talsma and Hallam 1980).

Compaction testing

The relationship between BD and soil moisture following a standard compactive effort (25 blows of the hammer) was determined using the Proctor test (Felt 1965; Standards Association of Australia 1977). Soils from all sites and depths were tested to determine critical moisture content. The compaction apparatus was constructed using a 100 mm diameter mold with a 2.5-kg hammer of 50 mm diameter falling 300 mm. Curves of BD against moisture content were derived, and critical moisture content was determined.

Analysis

Data was analyzed using GENSTAT® for analysis of variance and regression analysis. For analysis of variance, incomplete sets of data were treated as missing data for calculation of the interaction effects of site × number of machine passes, site × soil depth, and number of machine passes × soil depth. The mean of the four BD replicates from each sample was used.

Results

Bulk density changes with machine traffic

Soil type, the number of machine passes and soil depth all significantly affected the change in BD. A significant interaction between site and soil depth indicated differences between dry and wet forest sites in compaction through the soil profile, while the lack of interaction between site and number of machine passes indicated a similar pattern of compaction with machine traffic (Table 5).

On average 62% of the compaction of the surface 10 cm soil layer occurred after a single machine pass with steady increases with subsequent traffic. In the 10- to 20- and 20- to 30-cm layers, compaction increased up to the third pass, achieving 80–95% of the final compaction, and then little

Table 1. Site type, vegetation, and site descriptions of the six study areas.

Coordinates	Site type	Tree species	Geology	Soil type	Average annual rainfall (mm/year)	Altitude (m)	Logged	Mean soil moisture (%, w/w)
Gould's Country								
148°07′E, 41°07′S	Dry forest with low rainfall	*Eucalyptus amygdalina* Labill.	Granite	Hapludult	1100	280	Feb., July	14, 22
Forester								
147°40′E, 41°26′S	Dry forest with low rainfall	*E. amygdalina*	Devonian–Silurian sediments	Hapludult	900	180	Dec., Oct.	31, 33
Rose's Tier								
148°38′E, 41°26′S	Wet forest with high rainfall	*Eucalyptus delegatensis* R.T. Baker	Granodiorite	Haplohumult	1300	880	Apr., May	39, 42
Gad's Hill								
146°12′E, 41°36′S	Wet forest with high rainfall	*E. delegatensis*	Basalt	Eutrudox	1200	660	Mar., Sept.	41, 79
Picton								
146°40′E, 43°02′S	Wet forest with very high rainfall	*Eucalyptus obliqua* L'Herit., *Nothofagus cunninghamii* Hook.	Dolerite	Hapludalf	1800	220	August	90
Sumac								
145°04′E, 41°17′S	Wet forest with very high rainfall	*Eucalyptus nitida* Hook., *E. obliqua*, *N. cunninghamii*	Precambrian orthoquartzite and mudstone sequences	Endoaquept	2100	220	April	30

Table 2. Soil profile descriptions for the s sites used in the study.

Depth (cm)	Horizon	Description
Goulds Country		
0–2	A_{11}	Black loam
2–15	A_{12}	Very dark grey sandy clay loam; quartz gravel 40–50%
15–30	A_2	Dark brown fine sandy clay loam; quartz gravel > 30%
30–60	B_2	Mottled dark yellowish brown, yellowish brown sandy clay; quartz gravel 15%
60+	B_{21}	Mottled yellowish brown, dark yellowish brown sandy clay to light clay; quartz gravel <10%
Forester		
0–2	A_{11}	Black loam
2 7	A_{12}	Black silt loam
7–17	A_2	Brown silty clay
17–80	B_2	Brown light medium clay
80–90	B_{21}	Dark yellowish brown light medium clay
90+	C	Weathering mudstone
Roses Tier		
0–2	A_{11}	Black loam
2–9	A_{12}	Very dark brown loam fine sandy; quartz gravel 75%
9–20	A_2	Very dark greyish brown sandy clay loam
20–45	B_2	Dark yellowish brown sandy clay
45+	C	Weathering granodiorite
Gads Hill		
0–5	A_1	Dark reddish brown loam
5–20	A_2	Very dark brown clay loam
20+	B_2	Dark yellowish brown light medium clay
Picton		
0–3	O	Litter and organic layer
3–10	A_{11}	Dark reddish brown loam, fine sandy
10–13	A_{12}	Very dark grey silt loam
13–18	A_2	Dark greyish brown silty clay loam
18–60	B_2	Yellowish brown silty clay
60–80	B_3	Yellowish brown light to light medium clay
80+	C	Weathering dolerite
Sumac		
0–2	O_1	Undecomposed organic layer
2–4	O_2	Organic matter in various stages of decomposition
4–10	A_1	Black fine sandy loam
10–23	B_2	Very dark grey sandy clay loam
23–60	C	Compacted gravely silt and sandstone; dark blueish grey weathered material

thereafter (Fig. 1*a*). Comparison of compaction between dry-forest and wet-forest soils showed a similar pattern of increasing BD despite very different initial BDs (Fig. 1*b*). A pattern of a substantial increase in soil strength after one machine pass followed by a diminishing increase up to 16 passes was found on most sites studied (Fig. 1*c*).

Bulk density and soil strength under dry forest

A single machine pass on the dry soil at Goulds Country increased BD of the 0- to 10-cm soil by about 22% and at Forester by 30%. In the 10- to 20-cm layer, the increase in BD was 9% for Goulds Country and 17% at Forester. Bulk density increased only slightly from the first to the third pass and not significantly after that. There was no significant compaction in the 20- to 30-cm soil under dry forest. Soil strength increased significantly after the first pass, averaging 50% for the Goulds Country soil and 22% for the Forester soil. There were only small increases in soil strength beyond

Table 3. Visual assessment classification system for soil damage caused by logging (Wronski 1984).

Classification of skid trail	Description of damage
Primary	Removal or displacement of topsoil by gouging, puddling, and mixing of soil horizons; rutting into the B horizon
Secondary	Topsoil compacted in situ; minor rutting in top of A horizon
Tertiary	Removal of litter layer; minor gouging of A horizon

Table 4. Machine type and characteristics, average log volume, and skid-trail slope for each study area.

Site	Machine type	Ground pressure (kPa)	Chains	Slope (%)	Log size (m^3)
Goulds Country	Caterpillar 518 skidder	61	Front wheels	5–15	1.2
Forester	Timberjack 550 skidder	53 (front) 67 (rear)	No chains	10	1.2
Roses Tier	Clark 668C skidder	71	Front wheels	10	1.6
Gads Hill	Clark 668B skidder	71	Front wheels	5	1.6
Picton	John Deere 740 skidder	81	Front wheels	18	1.8
Sumac	Alison Chalmers H.D.16 dozer	71	na	10	1.8

Note: Ground pressure values (static) are quoted by the manufacturer on standard rubber tires or tracks. na, not applicable.

Table 5. ANOVA for soil bulk density by site, machine pass, and soil depth for six sites, two under dry forest, two under wet forest with high rainfall, and two under wet forest with very high rainfall, for up to 21 passes and 3 depths.

Source	SS	df	MS	F	p
Site	11.06	5	2.213	19.26	0.007
Major plot error	0.46	4	0.115		
Machine pass	0.91	6	0.152	15.76	0.000
Depth	3.57	2	1.784	182.31	0.000
Site × pass	0.32	30	0.011	1.10	0.356
Site × depth	0.42	10	0.042	4.15	0.000
Pass × depth	0.11	12	0.009	1.01	0.445
Residual	1.03	107	0.010		
Total	17.88	176			

Note: The machine pass data is sequential in nature, but analysis demonstrated nonsignificant autocorrelation.

the first pass. Assessed visually, neither of the skid-trails deteriorated past second-degree disturbance. Deterioration to second-degree disturbance occurred at around the 10th pass. There was little difference in soil moisture conditions between the summer and winter logging on either site. With winter logging, deterioration of the skid-trail (assessed visually) occurred slightly earlier.

Bulk density and soil strength under wet forest on high rainfall sites

For soils under high rainfall, BD in the 0- to 10-cm soil layer increased by an average of about 30% following the first pass of a machine. At lower depths, the increase in BD was slower, but most compaction was achieved in the first three passes. Soil strength increased by an average of about 25% following the first machine pass increasing to about 40% after the third pass. There was some further increase in soil strength with more passes. Following 21 passes, the soil at Roses Tier on granodiorite had higher BD but lower soil strength than the soil at Gads Hill on basalt. Visual assessment of the skid-trails showed deterioration to second degree damage by the 15th machine pass. With winter logging, visual deterioration occurred earlier.

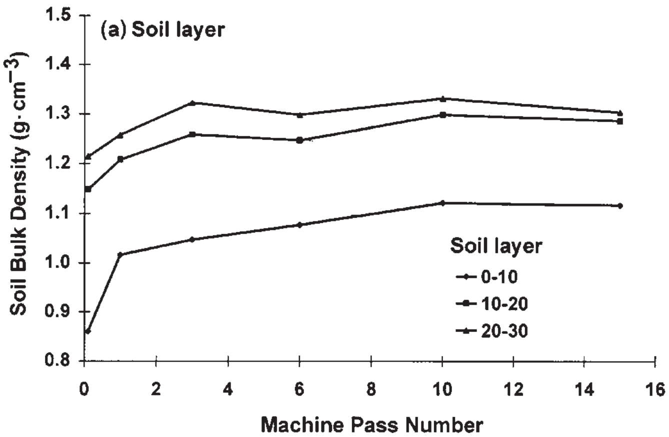
Bulk density and soil strength under wet forest on very high rainfall sites

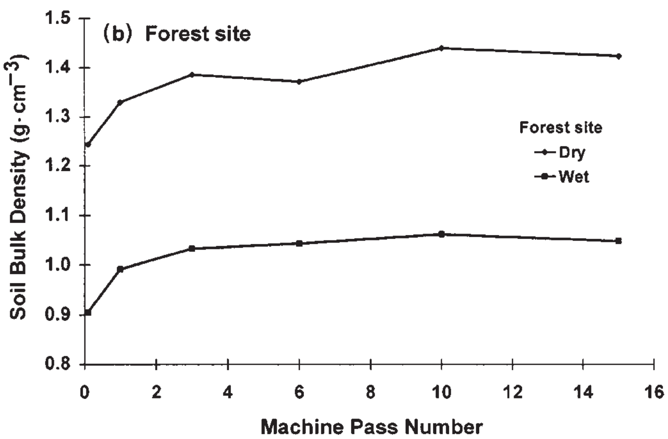
At Picton, significant compaction occurred on the first machine pass. Between the first and third pass, the 0- to 10-cm soil layer along the wheel ruts was displaced by the harvesting traffic to either the middle or the sides of the skid trail. Between the third and the sixth pass, the 10- to 20-cm layer and half of the 20- to 30-cm layer was displaced. At Sumac, soil compaction increased until the 6th and 10th passes. Soil strength increased significantly, by 167%, following the first machine pass at Picton. Further traffic increased strength linearly but at a reduced rate. At Sumac following the first pass, soil strength decreased significantly by 37% before increasing with a further two passes to a level still below the control. Beyond the third pass, the increase was linear and gradual until primary damage was sustained. The soils in the very high rainfall site deteriorated to primary visual damage during the course of the trial. At Picton the skid trail had deteriorated to second-degree disturbance after the first pass and to primary damage after a further two passes. At Sumac the skid trail deteriorated to second-degree damage between the 6th and 10th passes and primary damage between the 15th and the 21st passes.

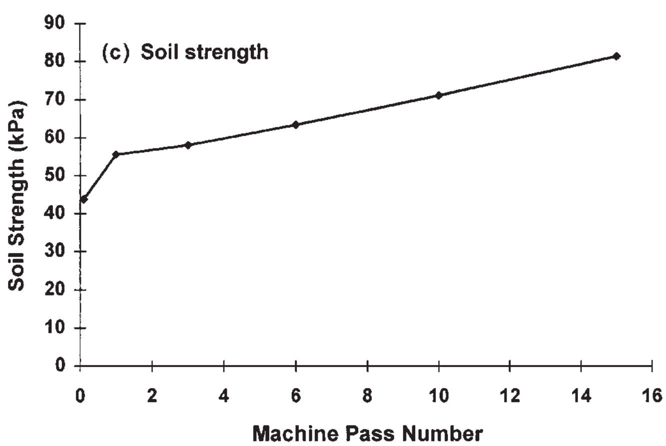
Bulk density and soil organic matter

For the six experimental sites, BD was significantly negatively related to OM (LOI) (R^2 = 0.85) (Fig. 2). Following 15 passes of a laden logging machine (six for Picton) the slope of the relationship between BD and OM remained the same as for 0 passes. However, there was a significant move in the level of the relationship (p < 0.01), and BD had

Fig. 1. Mean soil bulk density for four sites (two dry forest and two wet forest), of (*a*) three soil layers and (*b*) wet and dry forest sites, following up to 15 passes by a laden logging machine. (*c*) Mean soil strength for five sites following up to 15 passes.







increased by an average of 0.17 g·cm^{-3} (Fig. 2). Bulk density before operations and BD following 15 machine passes were significantly related (R^2 = 0.83).

Site relationships

At all sites, OM (LOI) content was significantly higher and BD significantly lower, in the surface 10 cm of soil than in the 10- to 20-cm or 20- to 30-cm levels. There was a weak but significant positive relationship of OM with rainfall ($R^2_{0-10\mathrm{cm}}$ = 0.15 and $R^2_{10-30\mathrm{cm}}$ = 0.26) and a significant negative relationship of BD with rainfall ($R^2_{0-10\mathrm{cm}}$ = 0.45 and $R^2_{10-30\mathrm{cm}}$ = 0.58).

Standard compaction test

The response from all soil types, to the standard compaction test, was similar with BD increasing with moisture content until a critical level (critical moisture content) before decreasing with further moisture increases. The compacted BD was strongly related to the undisturbed BD (R^2 = 0.77) for all six soils and depths (Fig. 3). Across the soil types, a strong inverse relationship existed between BD and the critical moisture content (Fig. 4*a*). Similarly, a strong inverse relationship was recorded between BD and OM (R^2 = –0.55). A strong positive relationship was recorded between OM and the critical moisture content (R^2 = 0.57) (Fig. 4*b*).

Saturated hydraulic conductivity

Saturated hydraulic conductivity showed a general pattern of reduction with increasing compaction for each soil, but there was no overall relationship with BD. Soils formed on granitic parent material, which had substantial gravel content (Table 2), had higher rates of hydraulic conductivity, and resisted change more, than those soils formed on finer grained parent materials. On five of the six sites, saturated hydraulic conductivity decreased to less than 10% of undisturbed flow following an increase in BD equivalent to 15–21 machine passes. On the majority of the 0- to 10-cm soils, increasing BD equivalent to the first machine pass saw a sharp reduction in saturated hydraulic conductivity of greater than 50%. No trend was apparent between the extent of decrease in saturated hydraulic conductivity and soil depth with similar decreases occurring in the lower depths as occurred at 0–10 cm.

The Sumac soil had moderately slow saturated hydraulic conductivity deteriorating to very slow with compaction. The Roses Tier soil deteriorated from very rapid to moderately slow, while the Gads Hill soil deteriorated from moderate to very slow. Of the soils under dry forest the saturated hydraulic conductivity remained moderate at Goulds Country, while for the Forester soil it deteriorated from moderate to slow.

Discussion

Machine traffic and compaction

Machine type, ground pressure, machine speed, and wheel slippage were all factors affecting soil damage (Murphy 1982; Meek 1996). In the research here, the ground pressure, of 53–81 kPa (Table 4) was applied during straight even trafficking over the trial area. This minimized complications of vibration, point loading, and shearing, resulting in a clear picture of compaction effects. A similar extent of compaction, averaging 0.17 g·cm^{-3} increase in BD, was recorded for all six field sites investigated in this research, despite substantial site and soil differences, including different initial soil BDs. The increases in BD recorded were comparable with those reported by other workers (Froelich 1972; Dickerson 1976; Allbrook 1986; Incerti et al. 1987). However, the compaction was slightly less than the 0.22 g·cm^{-3}

Fig. 2. Soil bulk density, after 0 and 15 passes of a laden logging machine, against soil organic matter, estimated by LOI, for three soil layers (0–10, 10–20, and 20–30 cm), for six soils over a range of rainfall and forest types.

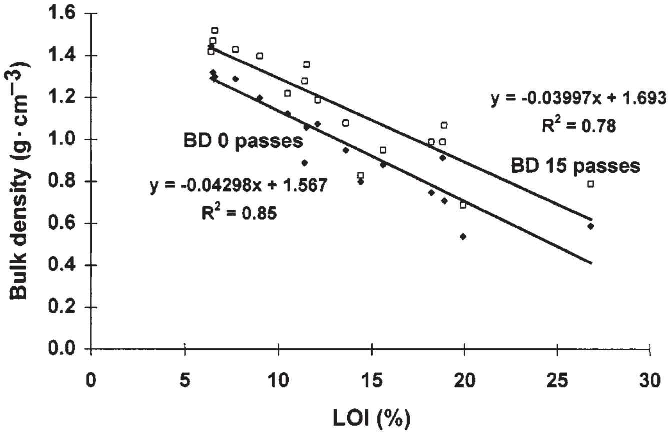


Fig. 3. Soil bulk density of soil compacted using the Proctor test against undisturbed soil bulk density, for three soil layers (0–10, 10–20, and 20–30 cm), for six soils over a range of rainfall and forest types.

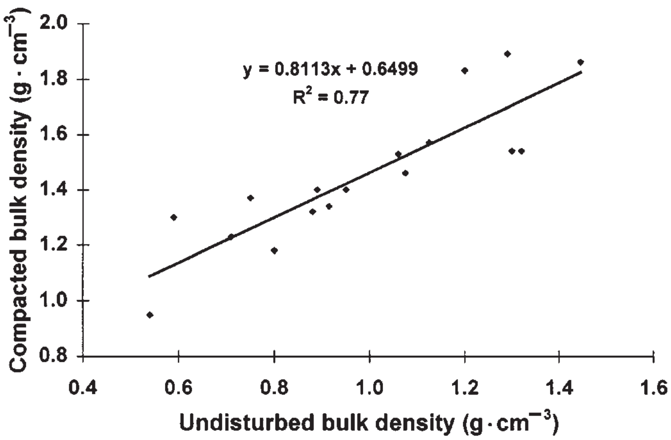
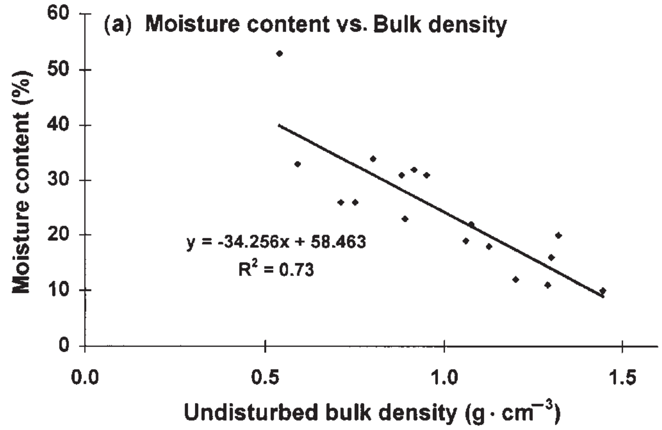
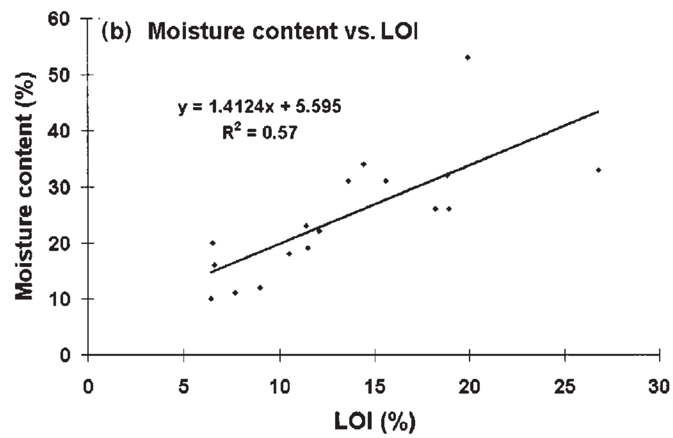


Fig. 4. Critical moisture content against (*a*) undisturbed soil bulk density and (*b*) soil organic matter, estimated by LOI, for three soil layers (0–10, 10–20, and 20–30 cm), for six soils over a range of rainfall and forest types.





increase measured on major skid trails on silt loam soils where similar machinery was used (Reisinger et al. 1992).

As all soils showed a similar total increase in BD, percent increases were greater on soils with initially lower soil BDs. Percent increase in BD has been suggested as a sustainability index, but this may unnecessarily limit activities on sites of initially low BD under wet forest, compared with sites under dry forest, where initial BDs are much higher. A small increase in BD under dry forest may lead to significant loss of macropore percentage and seriously reduce forest growth, while under wet forest a much larger increase, either percentage or absolute, might be of little consequence (Miller et al. 1996). A large data base for a range of forests, soils, and climatic situations will be required to determine the extent and importance of these changes.

The decision of whether to confine logging traffic to a limited network of defined skid trails or to disperse traffic as widely as possible depends on the amount of soil damage, compaction, or disturbance achieved with a few passes, compared with many passes. The situation will vary depending on the type of forest being logged, the machine used, and the availability of surface slash to dissipate the machine load. On the trial sites here most compaction occurred after few passes of a laden logging machine, with 62% of compaction in the first 10 cm of soil achieved after only one pass and 80–95% of the final compaction to 30 cm depth after only three passes. On some soils compaction continued with further passes, but the rate of compaction decreased. Similar results have been recorded elsewhere (Hatchell et al. 1970; Wingate-Hill and Jakobsen 1982; Soane 1986). Shetron et al. (1988) reported no difference between the BDs of low- and high-intensity skid trails indicating that initial compaction following light traffic was sufficient to increase soil strength to a level that would oppose the applied stresses of heavier traffic. The rapid increase in compaction was associated with a reduction in the volume of macropores (Froehlich 1972; Incerti et al. 1987). For the forests studied here, logging using a defined skid-trail system, confining traffic to a minimum proportion of a logged area, would be the recommended method. Probable long-term reductions of productivity of a limited proportion of a logged area will be more acceptable than the risk of substantial overall damage.

Once initial compaction was complete, with destruction of the majority of macropores, further compaction was resisted by the increasing soil strength and an increasing proportion of the applied forces were transmitted to lower depths. This process was considerably slower than the initial compaction process and corresponded to the declining increase in BD after the first few passes and the lag in BD increase displayed by the lower soil depths (Shetron et al. 1988). The effects of compaction normally dissipated with depth as surface layers directly opposed the stresses applied by the logging machine, with the machine contact pressure the principal factor affecting the degree of compaction. Compaction of lower soil layers by rubber-tired skidders was directly affected by tire contact area, the width of the tire contact, and the total load carried by the tire (Porterfield and Carpenter 1986).

The effect of traffic on BD declined with increasing soil depth, to 30 cm, on dry forest sites and wet forest sites under high rainfall but not under very high rainfall. Compaction would be expected to lower depths, than the 30 cm investigated here, under wet forest. On a West Australian podsolic soil, Schuster (1979) recorded compaction down to 40 cm on primary skid trails. On wet forest site under very high rainfall the forces applied by logging machinery resulted in profile disturbance (soil displacement) after 6–15 passes. In this situation it is likely that the soil moisture of the soil layers directly opposing the forces was higher than the critical moisture content. At moisture contents higher than the critical moisture content, soils have decreased ability to withstand the applied forces and thus deformation, in the form of profile disturbance, results rather than soil compaction.

Compaction was also likely to increase erodibility of soils, increasing clay mobility and waterlogging (Herbauts et al. 1996; Rab 1996). The greatest impact on soils from logging were often seen under wet conditions and following the heavy traffic of a number of passes. Compaction occurred after a few passes and was not substantially affected by moisture conditions. Soil displacement occurred more easily under wet conditions and accounted for the highly visual damage associated with logging.

Soil and site factors affecting bulk density and compaction

The environment under which soils had formed played a major role in determining the BD of the undisturbed soil. The environment, affecting the weathering of primary minerals, and the type of vegetation interacted to influence OM levels. Organic matter has influenced BD. In this trial, soils on low rainfall sites under dry forest had lowest OM content and highest BDs, while soils from very high rainfall sites under wet forest had highest OM content and lowest BDs.

Compaction by traffic (R^2 = 0.83) or standard compaction tests (R^2 = 0.77) were both strongly related to the original BD over the range of the six soils investigated. This indicated that strength to resist applied force developed in a similar manner across a range of soils. Soils under dry forest and soils formed on coarser gravelly parent material resisted compaction more than soils under wet forest or finer grained soils. Under dry forest there was little compaction of the 20- to 30-cm layer indicating existing strength sufficient to resist compaction. The strength of the deeper soil layers under dry forest is a legacy of a higher initial BD. Compared with higher rainfall sites, the higher initial BDs of the dry forest is a reflection of lower OM resulting from a lower rainfall forest type. The lower rainfall restricts aboveground plant biomass and belowground plant and microbial biomass. Corns (1988) also determined that coarse-textured gravely soils resisted compaction. Meek (1996) found that, on sands, BD stabilized after a few machine passes, while on clays, effects continued to increase. Smith et al. (1997) found that those soils with 5–10% LOI and 50–70% clay plus silt underwent greatest compaction. Local geology affected particle-size distribution and so compactability.

Mechanical compaction and soil strength

Maximum BDs, estimated using the 25-blow Proctor test, were much higher than those measured in the field trials. The results indicated that forces applied by the logging machinery investigated in this trial were not sufficient to compact soils to anywhere near maximum BDs. The BDs measured by the Proctor test might be approached under extreme conditions of compaction that could occur from point loading or inappropriate machines. In comparison with logging trials, overestimation of the maximum BD obtained using the 25-blow Proctor test have been reported by Murphy and Robertson (1984) and Froelich et al. (1980). They concluded that the 25-blow Proctor test was an indication of BD levels obtainable following extreme compactive efforts, which were not often experienced with forest harvesting. A 10-blow Proctor test only slightly overestimated the maximum BD occurring on high-intensity skid trails (Sidle and Drlica 1981). Despite the limitations of the Proctor test it was useful for studying compaction – soil moisture relationships and determining the critical moisture content. This critical moisture content was higher for soils from wet forest, with high OM content. This compensated to some extent for the wet nature of these forests. However, the results also imply that logging should be completed under drier conditions to minimize compaction. To minimize the risk of profile disturbance, the location of log landings and major skid trails should be in areas that have better internal and surface drainage (i.e., higher in the landscape).

Across the sites, soil strength at the completion of the trial ranged from 44 to 182 kPa. In a number of trials the strength at which plant roots were inhibited was variable depending on soil type, OM content, moisture content, and plant species. At a soil strength of 400 kPa, Wasterlund (1985) reported a 54% decrease in leaf and shoot growth of *Picea abies* (L.) Karst. as compared with those grown on uncompacted soil. Penetration of *Pinus radiata* Donn ex D. Don roots was severely restricted at a soil strength of 3000 kPa (Sands et al. 1979). The strengths obtained in this trial fell well below these levels and, assuming that eucalypts show a similar response to compaction as pines, should not severely restrict root growth. However, other properties altered by compaction such as destruction of macropores and its effect on aeration and drainage are likely to restrict tree growth.

Hydraulic conductivity

The size of the reductions in hydraulic conductivity reported here were similar or greater than those reported elsewhere (Blake et al. 1976; Wronski 1984; Incerti et al. 1987; Huang et al. 1996). Goulds Country had smaller total reductions in hydraulic conductivity than the other sites for an equivalent increase in machine pass number. Goulds Country soils with their high coarse sand and gravel contents had the largest particle-size distribution of any of the soils studied and the soil resisted destruction of the macropore system during compaction enabling moderate flow rates to be sustained.

On most of the soils, the greatest reduction in hydraulic conductivity occurred in the 0- to 10-cm soil layer. This would have an effect on infiltration of water into the profile by reducing the infiltration wetting front (Hillel 1971). On loamy soils formed on loessic parent material, Herbauts et al. (1996) determined a reduction in macropores (pf <2.5) from 15 to 6% of soil volume, below the value of 10% that they considered as the threshold for root viability. This induced temporary waterlogging and increased clay dispersability. The effect of compaction on hydraulic flow was significant in itself; however, any pudding or destruction of the surface soil structure would tend to seal the soil surface further depleting water infiltration. If the surface infiltration rate was lower than rainfall events, waterlogging and surface runoff would occur (Rab 1996). Waterlogging would persist to a depth where a significant reduction in hydraulic conductivity had occurred. Extended periods of waterlogging would impede aeration of the soil depleting oxygen supplies for root respiration and producing anaerobic processes altering the nutrient status of the soil (Russell 1973). Surface water runoff as a result of reduced infiltration would increase the risk of soil erosion.

Effect of soil moisture and visual damage

On most soil types, the greatest amount of compaction, with associated increased soil strength and decreased hydraulic conductivity, occurred whilst the trail was classed as third-degree damage. Primary and secondary damage highlighted profile disturbance and displacement of topsoil as opposed to direct compaction. Greater damage to wet soils was associated with deformation and displacement, rather than with compaction in situ. Displacement also exposed subsoil that, in the soils investigated, also had higher BDs than the surface soil. The removal of surface horizons through profile disturbance (primary damage) removes soil layers that generally have the highest fertility and best soil structure. It is likely that subsequent revegetation of these areas will be impeded.

In this and other studies, soils with higher moisture contents visually deteriorated following fewer machine passes (Froelich 1972; Murphy 1982). At Picton, where soil moisture was high, the soil deteriorated visually to primary damage after only three machine passes. Higher moisture contents reduced soil strength. Because there was appreciable reductions in hydraulic flow, at all depths measured, high moisture contents could be expected for longer periods. High moisture contents in the soil profile, whilst being trafficked, increased the chance of soil deformation and displacement as was witnessed at Picton and Sumac. With increasing moisture content, cohesion within and between aggregates decreased because of an increased distance between the clay-polyplates and the swelling of aggregates (Koenigs 1963). This increased until critical moisture content (approximated by the Proctor test). Therefore, the resistance of the soil to applied stresses was low, and excess energy was able to reorientate soil particles causing deformation. At this stage, soil was easily displaced from the skid trail via lateral movement (Koenigs 1963). The removal of surface soil horizons may result in regeneration difficulties and reduce growth of vegetation that does regenerate.

At higher moisture contents, soil strength decreased, and this decreased the bearing capacity. If the soil was wetter than the critical moisture content, the presence or absence of surface water made little difference to the vulnerability of the soil to puddling and primary damage. It was water within the solum that reduced soil strength and bearing capacity not surface water (Koenigs 1963). Surface water was, however, a good indication of a waterlogged soil (Rab 1996).

The immediate and long-term impacts of compaction and profile disturbance on sustainability and forest growth need to be determined for a number of soils. Further work will concentrate on these issues.

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